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Feasibility Study of Zero Carbon Domestic Building in the UK

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ABSTRACT

This paper evaluates the technical feasibility of an existing domestic building in the UK to achieve zero carbon emission. Local weather condition and the initial building energy performance are analysed to provide the guide for building refurbishment and the available renewable energy sources. Various passive design strategies are adopted for building refurbishment, such as building envelope improvements, shading device and efficient appliances. Solar and wind energies are captured to provide heating and electricity for the building, these include solar collector, PV panel and wind turbine. EnergyPlus simulation software is employed to investigate energy performance of the building with different passive design strategies and renewable energy systems. The research results show that applying passive design components into the building reduces the annual energy consumption of 69.4%. The renewable energy systems consist of 4.26 m^2 solar collectors and a 2.5 kW wind turbine; they can produce enough heat and electricity to meet the building energy demands. It is possible to achieve the zero carbon domestic building in the UK with the passive design strategies and the renewable energy sources. In addition, the building is not only the zero carbon emission, but makes a contribution to CO_2 reduction of 718 kg per year with surplus electricity output.

1. INTRODUCTION

The United Kingdom government has laid out carbon target to reduce its emissions by at least 80% from 1990 levels by 2050, and renewable energy target to obtain 15% of the gross energy consumption from renewable sources by 2020. In the building sector, the Code for Sustainable Homes is a step change in sustainable buildings, the level 6 in the Code requires that the energy standard achieves a completely zero carbon home, but it is applied only for new home performance.

Zero carbon building refers to an energy efficiency building with on-site production which converts the building from an energy consumer to a producer (Griffith *et al*., 2007). The zero carbon building normally implies that electric power is delivered from the grid when there is no enough renewable energy generated, and then the building exports the power to the grid when the renewable systems have excess power produced (Wang *et al*., 2009). The object of zero carbon building is not only to mitigate the energy demands of a building with passive strategies, but also to design low carbon techniques and renewable energy systems for energy balance. Biaou *et al*. (2006) applied TRNSYS 15.3 to simulate a zero net energy home in Montreal. The results illustrated that the building equipped with 85.4 m^2 of PV panels and a 2.5 tons of ground source heat pump is possible to achieve a zero net energy house. Wang *et al*. (2009) simulated a zero energy house in Cardiff with EnergyPlus and TRNSYS 16. The EnergyPlus is employed to investigate the effect of building materials, window sizes and orientations, and TRNSYS is applied to find the potential of zero energy building with renewable electricity, solar hot water and energy efficient heating systems. Zero carbon building can be achieved by a tightly integrated combination of building envelope improvements and low carbon heat and power technologies (Zero carbon hub, 2013). A hierarchical approach to achieve zero carbon refurbishment is developed (Xing et al., 2011), it includes retrofitting fabrics, efficient equipments and micro generation. Retrofitting building fabrics is significant to reduce energy demand in building. For the existing wall, adding external insulation layer is a solution which has no influence on the indoor space (Xing *et al*., 2011). Cavity wall insulation is another solution that filled the insulation layer in the exterior walls. Using energy efficient appliances create a significant decline of electricity consumption. Zissis (2007) indicated that electrical lighting consumes about 30% of total electricity in the residential sector (Houri and Khoury, 2010). Micro generation is applied for zero or low carbon heat and power generation to meet the building energy demands. There are various micro generation technologies, such as wind, solar thermal, PV panel, hydro, and ground source heat pump. The most commonly used renewable technologies to meet the zero-energy target for on-site system are PV and solar thermal panels (Marszal *et al*., 2011).

This paper investigates energy performance of an existing domestic building in the UK and develops carbon reduction strategies in the building. The assessment is conducted to determine the technical potential of achieving zero carbon for the existing domestic building. Various carbon reduction strategies are carried out including building refurbishment with passive building components and application of renewable energy systems. In this study, EnergyPlus is used to produce a data set of energy performance for the domestic building in refurbishment strategies and renewable energy technologies.

2. WEATHER CONDITION ANALYSES AND INITIAL BUILDING DESCRIPTION

2.1 Weather Condition

The analyses of weather data and building are the primary step for zero carbon building design, because the analyses provide important guides for building refurbishment and renewable energy system selections. The building is located in city Hemsby. Hemsby is situated at 52.7° North latitude, 1.7° East longitude in the east of England. Heating, cooling and solar degree hours for this city are shown in Figure 1. The curves reflect that cooling is unnecessary except in June, July and August, but heating energy is needed even in summer months. For a whole year, the cooling degree-hour is 156 and the heating degree-hour is 68378 which indicate that the high demands for heating for buildings in Hemsby.

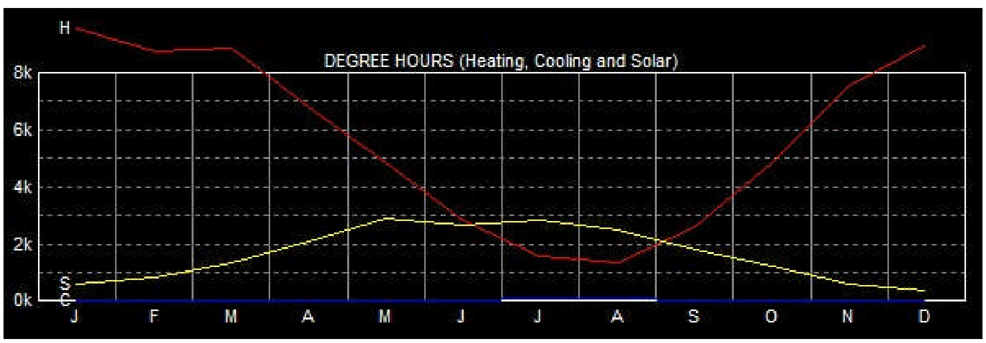

Figure 1: Heating, cooling and solar degree hours for Hemsby, UK

Solar radiation influences building heating and cooling loads. In winter, solar radiation makes a contribution to reduce the heating energy demands. On the other hand, solar radiation may cause overheating in summer. Monthly distribution of solar radiation is shown in Figure 2. Monthly solar energy accumulated on an area varies from 800 to 6300 Wh/m^2. The optimum orientation to receive solar radiation in Hemsby is 172.5° from north in clockwise direction; this provides the optimum installation direction for solar collector and PV panels.

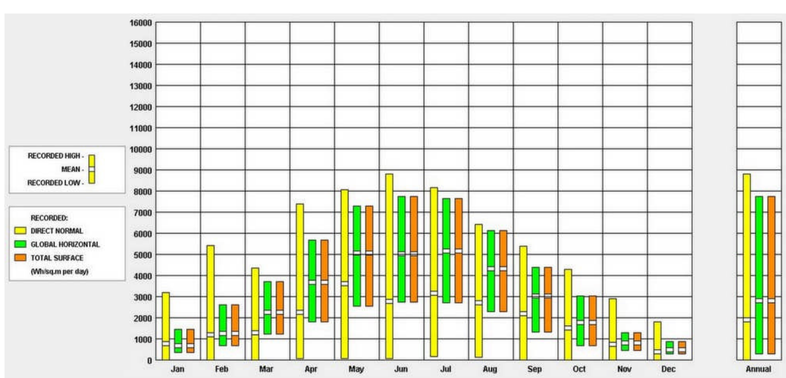

Figure 2: Monthly solar radiation distribution profile for Hemsby, UK

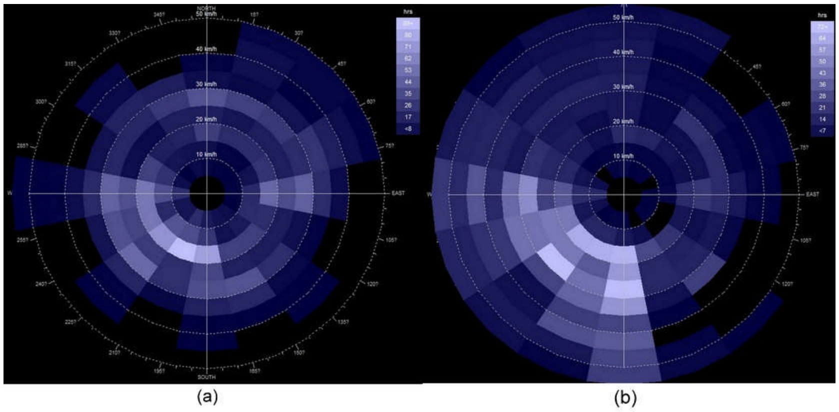

Figure 3: Wind rose profiles for Hemsby, UK. (a) Summer wind rose. (b) Winter wind rose

The prevailing winds for the whole year blow from southwest. The wind rose profiles of summer and winter which indicate wind directions and speeds are shown in Figure 3. In summer, the average speed of wind is about 4.8 m/s, and in winter the wind rose profile shows an average velocity of 7.1 m/s. During winter months, high value of wind speed may cause the increase of building heat losses, which can be prevented by highly insulated building envelope. On the other hand, significant wind resource contributes to improving electricity generation by wind power system.

2.2 Initial Building

A two-story domestic building is used for modelling and analysis in this study as shown in Figure 4. The orientation of the building is 15° west of south, and there is no shading from other buildings, the detailed layouts of the ground floor and first floor are shown in Figure 5. For the energy model, plant room is not included. Additionally, the Table 1 lists floor area and window area, as well as wall to floor and window to wall ratios. The fabric elements of the building are listed in Table 2. Each element consists of one or more layers, the material thermal proprieties and thicknesses of different layers are given as well.

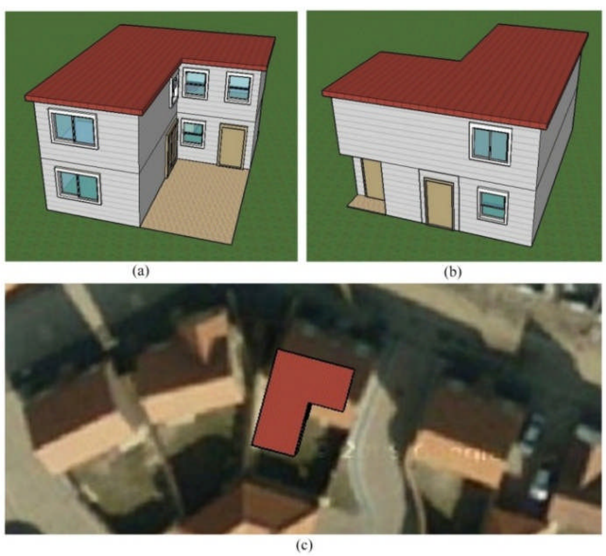

Figure 4: SketchUp model for the two-story domestic building in Hemsby
(a. viewed from south b. viewed from north c. viewed from top)

A packaged DX cooling with electric heating HVAC system is installed to provide heating and cooling (if cooling is required). According to the recommended comfort criteria for specific applications from CIBSE Guide A (CIBSE, 2006), the heating and cooling set point temperatures are 19℃ and 25℃. Since the systems are installed in the plant room, which is separated from the zone model of house, heat released by the HVAC system is not involved in the electric equipment heat gain. EnergyPlus software is used for energy simulation, and the results show that the annual heating and cooling energies required are 41.96 GJ and 0.10 GJ. For each square meter, heating and cooling demands are 137.44 kWh/ (m^2/yr) and 0.34 kWh/ (m^2/yr).

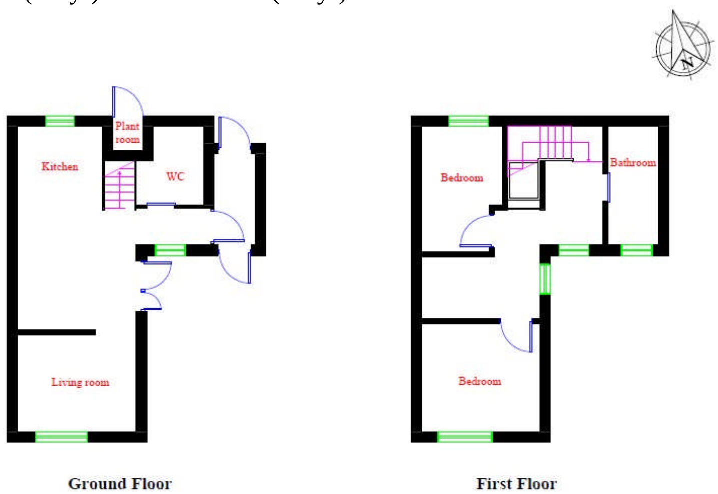

Figure 5: Ground and first floor plans

Table 1: Building dimensions

	Floor area, m2	Floor to ceiling height, m	Wall to floor ratio	Total window area, m2	Window to wall ratio
Ground Floor	41.05	2.4	1.99	3.74	0.046
First Floor	43.75	2.4	1.76	6.05	0.079

Table 2: Initial building elements and thermal properties of materials

Elements	Layers	Thickness, mm	Density, kg/m3	Sp. Heat, kJ/kg.K	Conductivity, W/m.K
External Wall	Concrete 1-4 Dry	10	2300	656.9	0.753
	Brick Masonry Medium	110	2300	836.8	0.711
	Air Gap	-	-	-	-
	Brick Masonry Medium	110	2000	836.8	0.711
	Plaster Board	10	1250	1088	0.431
Internal Wall	Plaster Board	10	1250	1088	0.431
	Air Gap	-	-	-	-
	Plaster Board	10	1250	1088	0.431
Roof	Asphalt Cover	6	900	1966	0.088
	Dense Concrete	150	2200	840	1.7
	Plaster Board	12	1250	1088	0.431
Floor	Plaster Board	10	1250	1088	0.431
	Air Gap	-	-	-	-
	Concrete	100	3800	656.9	0.753
	Concrete Screed	5	2000	656.9	0.753
	Ceramic Tiles	10	1900	656.9	0.309
Ceiling	Ceramic Tiles	12	3400	753.1	2.092
	Screed	25	950	656.9	0.209
	Concrete Floor	150	2300	656.9	0.753
	Air Gap	-	-	-	-
	Gypsum (Mineral)	12	2320	1088	1.297
Window	Glass Standard	6	2300	836.8	1.046
Door	Wood Oak White Live	40	825	2385	0.209

3. BUILDING REFURBISHMENT

3.1 Refurbishment Strategies

The passive design contains improving the performance of external wall, roof, floor, window and door, and adding shading device to reduce solar heat gain in summer. Thermal properties and refurbished wall layers are illustrated in Figure 6 where the insulation layer bonded with the brick masonry is highlighted in red. The insulation layer has a total thickness of 87.5mm and a low conductivity 0.019 W/mK.

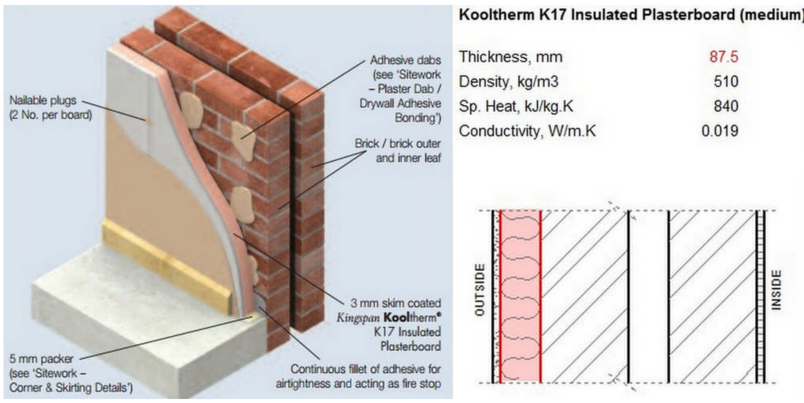

Figure 6: External wall structure and insulation thermal properties

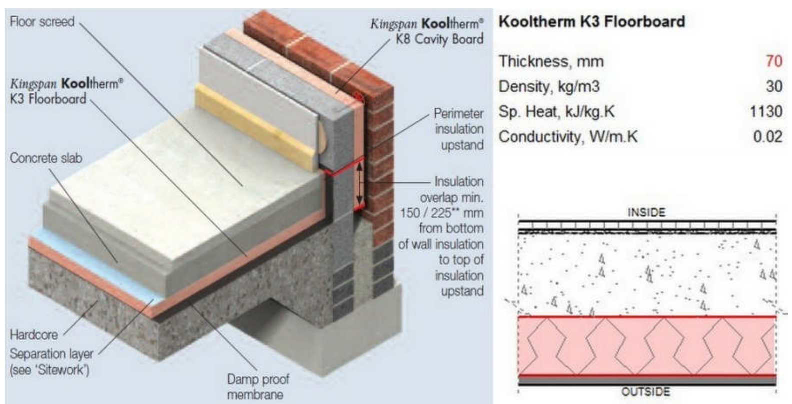

Figure 7: Ground floor structure and insulation thermal properties

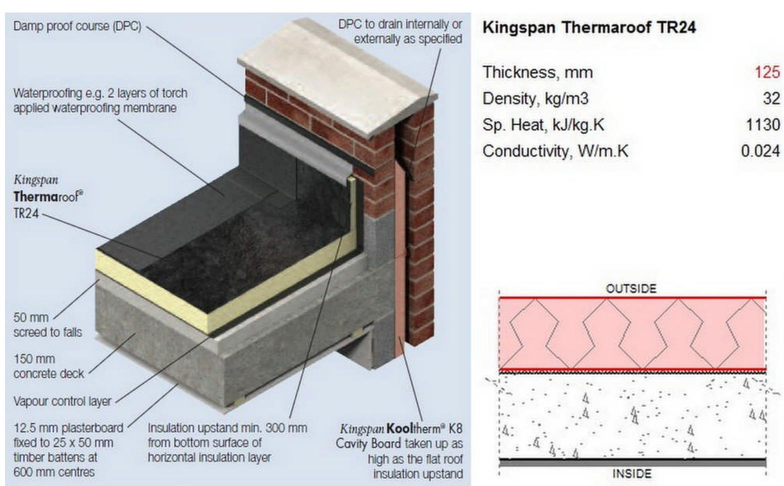

Figure 8: Roof structure and insulation thermal properties

Single layer insulation for solid concrete ground floor is applied, which is a low density floorboard. As shown in Figure 7, the 70 mm thickness Kooltherm K3 floorboard with a conductivity of 0.02 W/mK is added. For roof refurbishment, Thermaroof TR24 is applied as the insulation. Thermal properties of TR24 and construction of the refurbished roof are delineated in Figure 8. Single glazed windows are replaced by double glazed type which is a 4+12+4 mm filled with argon gas. The 4 mm clear glass has solar transmittance of 0.68, visible transmittance of 0.3 and U value of 3.7 W/m^{2}K. To improve the thermal performance of external door, the current door will be replaced by a 60 mm solid insulated core door which has a low U value of 0.8 W/m^{2}K. To reduce unwanted solar heat gain in summer, shading devices will be installed. Simple 0.4 m shading devices are added to the southwest facing windows for solar protection.

3.2 Energy Performance

The passive design strategy includes building component improvements for external wall, roof and floor, window and door. Heating energy demands for the initial building and building applied different strategies are shown in Figure 9. The refurbishment of external walls shows the most effective to reduce heating energy demands, while the refurbishment of window and door has relatively less efficacy. In total, refurbishment of external wall contributes to reducing annual heating energy demand of 15.8 GJ, the roof and floor improvements cause a decline of 9.98 GJ/yr., and refurbishments of window and door help to reduce 3.37 GJ/yr.

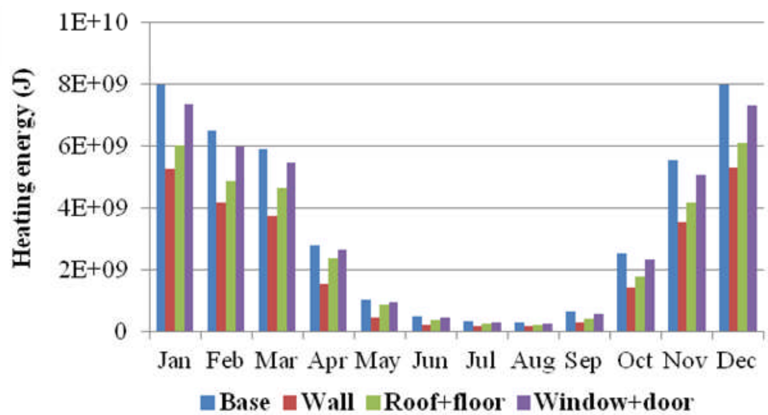

Figure 9: Heating energy demands for building applied different strategies

Monthly cooling energy demands are shown in Figure 10. The refurbishment may increase cooling energy demand that overheating in summer is becoming an issue, for example, the external wall improvement causes an extra cooling energy of 18 MJ in July. But roof and floor improvements contribute to reducing cooling energy of 61.8 MJ and window and door improvements reduce cooling energy 15.1 MJ in July. Annual cooling energy demands show that wall refurbishment increases 35.2 MJ cooling energy demands, roof and floor refurbishments help to reduce cooling energy demands of 89.1 MJ, and refurbishment of window and door promotes 24.9 MJ reduction of cooling energy demands. It can be found that envelope improvement of roof and floor makes a significant contribution to cooling energy decrease. The total energy saving for the passive design strategy is 69.4% as shown in Table 3.

Table 3: Energy saving

Improvement	Base	Refurbished	Saving from base
Wall	42.06 GJ/yr	26.33 GJ/yr	37.41%
Roor & floor	42.06 GJ/yr	32.00 GJ/yr	23.93%
Window & door	42.06 GJ/yr	38.67 GJ/yr	8.06%

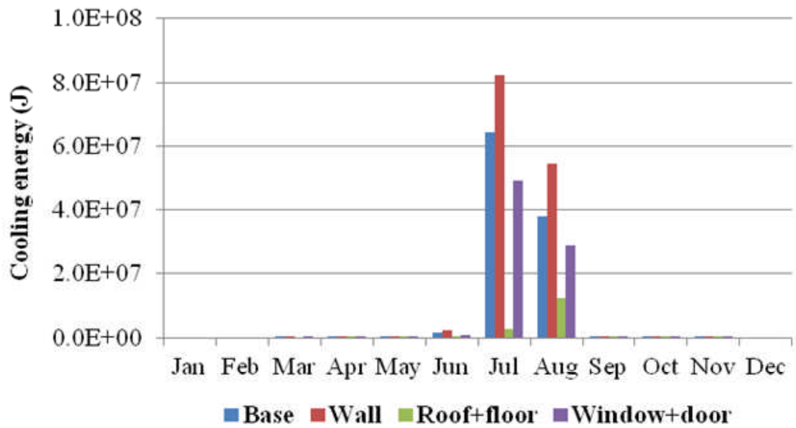

Figure 10: Cooling energy demands for building applied different strategies

4. RENEWABLE ENERGY SYSTEMS

4.1 Renewable Energy Systems

Renewable energy systems are essential for zero carbon building, solar thermal collector, photovoltaic and wind turbine systems are utilized and compared to find the optimal systems. Evacuated tube solar collector system is employed for the building. The optimum inclination of collector is South in the Northern Hemisphere (Adell, 1982), and the orientation between 30° east and 40° west of south are acceptable. For this building, the position and orientation of the solar collector array are shown in Figure 11 that solar collector array consists of 2 modules, and the specifications are illustrated in Table 4.

Table 4: Specifications for solar collector

Module	THERMOMAX HP200
Manufacturer	Kingspan Solar
Absorber area (m2)	3.021
Aperture area (m2)	3.23
ηo	0.727
α1 $(W \cdot m^{-2} \cdot K^{-1})$	0.85
α2 $(W \cdot m^{-2} \cdot K^{-2})$	0.0093
Heat transfer fluid	water
Vertical orientation	45°
Horizontal orientation	15° west of south

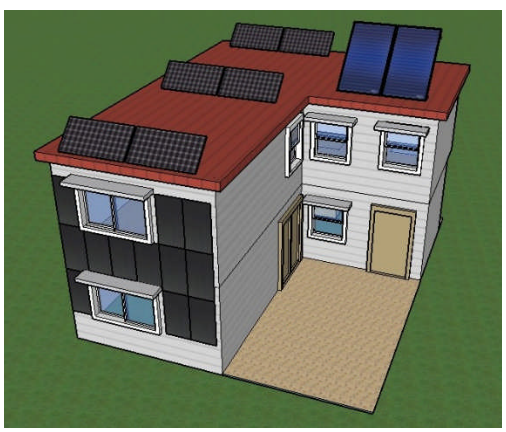

Figure 11: Solar collector and PV panels

The type of PV electric power system for this domestic building is PV grid back-up without battery backup capability. PV panel installation orientation and tilt are the same as solar thermal collectors. To avoid shading from the panel in front, only three rows are installed on the roof. Furthermore, facade integrated PV panels are mounted to the south-facing walls, as indicated in Figure 11. The monocrystalline silicon solar module is selected, and the size of PV panel is 1.28 m^2 and the specifications are listed in Table 5. Micro wind turbine Proven 2.5 with 11 meters tower kit is mounted close to the building, the turbine specifications are shown in Table 6.

Table 5: Specifications for PV module

Module	PLM-200 M72
Manufacturer	Westech Solar
Dimensions L, W, D (mm)	1580, 808, 40
Cell efficiency (%)	18.48
Module efficiency (%)	15.67
Rated power	200 Wp
Open circuit voltage (V)	44.6
Short circuit current (A)	5.72
Voltage at maximum power (V)	37.6
Current at maximum power (A)	5.32

Table 6: Specifications of micro wind turbine

Module	Proven 2.5
Manufacturer	Proven Energy
Rated power output (W)	2500
Cut in wind speed (m/s)	2.5
Survival wind speed (m/s)	70
Rated wind speed (m/s)	12
Rotor diameter (m)	3.5
Number of blades	3
Rated rotor speed (rpm)	300
Overall height (m)	11

In this study, two scenarios of on-site renewable energy systems are investigated to assess the potential for achieving a zero carbon building; one is solar collector and PV power generation system, the other is solar collector and micro wind turbine system.

4.2 Solar Collector and PV Power Systems

In this case, the solar collector only provides a part of domestic hot water energy, and the extra hot water is designed to be provided by an electronic mini instantaneous water heater. Monthly heat energy produced by the collector and the total amount of energy consumed by hot water plant are indicated in Figure 12. The average monthly heat energy produced by solar collector system is 1.04 GJ and the annual energy produced is 12.47 GJ which can provide 29.7% of total amount of heat energy requirement.

Since the extra water heating is supplied by a water heater, the energy should be provided by the electrical power generation system (i.e. PV system in this scenario). The electricity consumed by pumps, fans, equipment and lights should be generated by PV power system as well. A diagram indicated monthly consumption of each system is shown in Figure 13. Since large amounts of energy required for building heating in winter, more energy demands in winter months than summer months. The peak electricity requirement occurs in December. Nevertheless, electricity demand in summer months is relatively low, for instance, in May the total consumption is about 0.72 GJ. However, the electric power generated by PV system in winter is much less than in summer (as shown in Figure 14). The annual electricity can be supplied by the PV system is 8.12 GJ, while the annual electricity consumption for the domestic house is 15.46 GJ. Thus, there is 52.5% of the total electricity can be supplied by the PV system.

Figure 12: Heat production and consumption

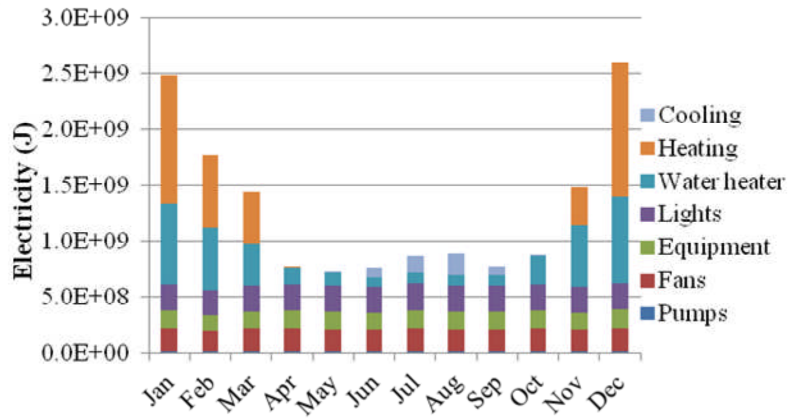

Figure 13: Monthly electricity consumption

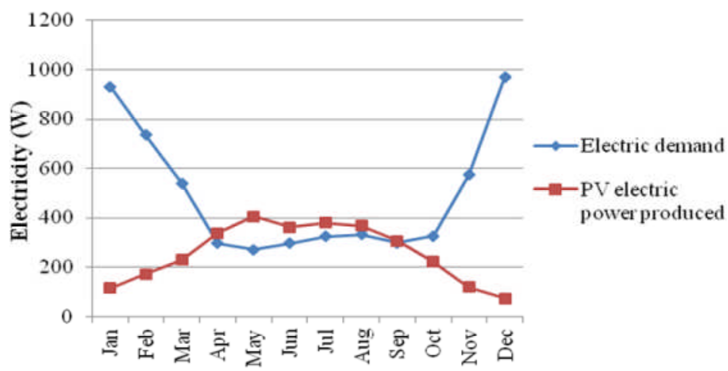

Figure 14: PV system electric power generation

4.3 Solar Collector and Micro Wind Turbine

In this case, solar collector system is the same as the previous, the heating energy produced by the collector is similar to the previous scenario and a 2.5 kW wind turbine is installed to replaces the PV system for electric power supply. Monthly electricity demand and wind turbine output are shown in Figure 15. The diagram shows wind turbine system produces enough power for the building in all months, except February. The annual electricity can be produced by the wind turbine system is 20.22 GJ, and the annual building electricity consumption is 15.46 GJ. There is an extra electricity generation of 4.76 GJ. In this scenario, the solar collector contributes 29.7% of annual heating supply and the wind power system contributes 130.8% of annual electricity requirement.

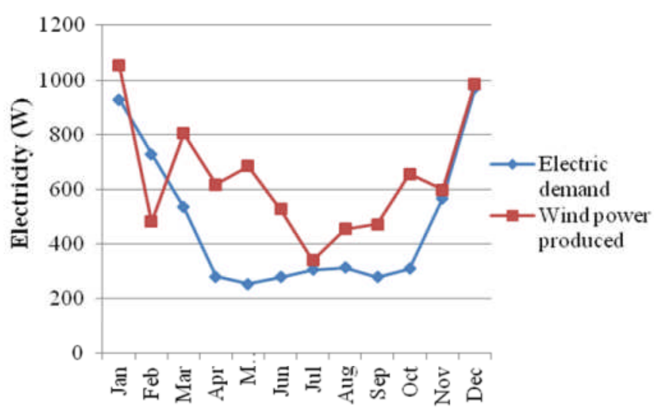

Figure 15: Wind turbine electric power generation

Carbon dioxide emissions can be determined. Since the electricity carbon dioxide emission factor is 0.543 kg CO_2/kWh, the CO_2 emissions of the first and second scenarios are 1106 kg/yr and -718 kg/yr. The results show that building installed PV panels consumes 7.33 GJ/yr. of extra electricity which should be delivered from the grid. Zero carbon building could be achieved when using wind power system.

5. CONCLUSIONS

The technical potential for achieving zero carbon emission domestic building with EnergyPlus simulation is assessed in this study, refurbishment strategies and renewable technologies are investigated. The local weather data and initial building energy demand are analyzed to identify the optimal solutions for building refurbishment and the available renewable energy sources. The comparison of applying various envelope improvements is presented, and the results shows that adding insulation material to external walls is the most significant strategy for mitigating energy demand. Adding 87.5 mm plasterboard to the external wall reduces the building annual energy consumption 37.41%. Applying all these solutions to the building can reduce 69.4% energy demand. Two scenarios of renewable energy systems for energy supply are evaluated, the first scenario consists of solar collector and PV power system, and the second includes solar collector and micro wind turbine system. Solar collector provides 29.7% of total heating demand for both scenarios. PV system in the first scenario generates 52.5% of total electricity consumption. Micro wind turbine in the second scenario produces 130.8% of annual electricity requirement. For the CO_2 emissions, 1106 kg/yr. CO_2 is emitted for the first scenario. The building applied the second scenario achieves zero carbon emission and contributes a CO_2 reduction of 718 kg per year.

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